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Biochar-Assisted Wastewater Treatment and Waste Valorization

Abhishek Pokharel, Bishnu Acharya and Aitazaz Farooque

Abstract

Biochar is the solid byproduct of pyrolysis, and its cascading use can offset the cost of the production and its use in application such as soil remediation. A wide variety of research on biochar has highlighted its ability to absorb nutrients, metal and complex compounds, filter suspended solids, enhance microorganisms' growth, retain water and nutrients as well as increasing the carbon content of the soil. Besides, sustainable biochar systems are an attractive approach for carbon sequestration and total waste management cycle. The chapter looks into such cascading use of biochar in wastewater treatment for recovering nutrients and improving the efficiency of activated sludge treatment and anaerobic digestion for producing biosolid with enhanced soil amendment properties.

Keywords: biochar, wastewater treatment, activated sludge treatment, anaerobic digestion, nutrient recovery, waste valorization

1. Introduction

Today, the global population continues to grow by 83 million annually and is predicted to be 9.8 billion in 2050 [1]. This increase in population will lead to higher demands of food, water, and energy, which have already been constrained due to the competing needs for limited resources in many parts of the world [2]. The challenges presented by climate change, pollution, and developing economy are posing significant pressure on food, water, and energy systems [3]. Efficient and integrated management of energy, food, and water resources could help address several of the biggest global challenges, such as climate change, sustainable economy, food security, environmental and social security [4, 5]. In the future, we will need increased food production, clear water sources, as well as alternative energy options with minimum resource utilization and ideally decreasing environmental impacts [6]. Work is underway to improve the food production chain as well as develop new technologies for renewable energy. So far less focus has been given to the water, especially to the management of the wastewater. There is a need for shifting the paradigm in the case of wastewater management from treatment and disposal to reuse, recycle, and resource recovery. With growing water scarcity and the fact that uncontrolled disposal of wastewater to the freshwater system is causing depletion of the system also stresses toward a change in mindset about wastewater management. This approach will prevent detrimental impacts on human health and ecosystem caused by the current handling methods. The next step toward a sustainable future will be wastewater treatment serving multiple purposes of treatment and recovery of resources like water, nutrient, and energy. The efficient wastewater management approach will see

a cascaded benefit in other sectors including production of fertilizers such as nitrogen and phosphorus. Phosphorus is obtained from ore called phosphate rocks. The quality and accessibility of currently available phosphate rock reserves are declining, and the cost to mine, refine, store, and transport them is rising [7, 8]. Similarly, the production of nitrogen and other mineral fertilizers is energy intensive as well as contributes to environmental pollution [3, 9]. The nitrogen fertilizer can leach to nearby water bodies leading to the phenomenon of eutrophication. The richness of nutrients in the water results in excessive growth of macroalgae and could lead to anoxic events and loss of aquatic system. Recovery of these nutrients from wastewater helps to close the cycle and reduce the amount of chemical fertilizer, directly contributing to the sustainability of food production.

One of the first indications of intentional nutrient recycling is documented 5000 years ago in rural Asia, where human excreta was used for fertilization of fields called “night soil” [10]. In the nineteenth and twentieth century with the industrial revolution, the population density became high, which gave rise to “Sanitation Revolution,” a transition from land-based to water-based disposal of human wastes. This disposal system changed the nutrient cycle from reuse to complete discard. Following the Industrial and Sanitation Revolutions, the Green Revolution that reformed agriculture largely abandoned organic fertilizers and put forth the mineral fertilizers [10, 11]. Furthermore, owing to the excessive population growth, producing enough food with only organic sources of plant nutrients has become impossible. Therefore, the need for mineral fertilizers is a true fact. Thus, many urban areas have dedicated wastewater treatment plant to remove the nuisance of human waste. But, it is becoming evident that future changes, particularly those associated with urbanization and population growth-related increase in volume of wastewater, add more stress to the wastewater system performance [12].

The greater dependency on fossil fuels in every sector is heavily contributing to global warming and climate change [13]. As an alternative, abundant biomass could play an essential role in reducing the dependency on fossil fuel as well as contribute toward sustainable development. Pyrolysis of biomass produces biochar and bio-oil. The bio-oil could be used as fuel to substitute the petroleum products with some upgrading that includes catalytic esterification and hydrogenation. The biochar could be used for energy and soil application [14]. Soil application helps in sequestration of carbon dioxide and subsequently supports food production. At present, the biochar application in soil remediation is not cost-effective. The financial feasibility could be improved by developing a cascaded use of biochar, as discussed in this chapter. The inherent properties of biochar make it suitable for (a) recovering nutrients from the wastewater, (b) improving the activated sludge treatment to reduce the energy use for aeration and to improve the settling ability of sludge, (c) increasing the energy recovery from sludge through anaerobic digestion, and (d) enhancing the quality of the biosolids for soil application. There are reports of biochar application having agronomic benefits in fertilizer management, yield, and soil biota [15–20]. Biochar, as a sound absorbent, also holds promise for low-cost wastewater treatment as an alternative to activated carbon [21–24]. The integrated use of biochar in wastewater treatment addresses the current issues with the management of wastewater. However, the benefit of using biochar varies with its type and characteristics, which depends on the biomass, and the pyrolysis conditions [25].

This chapter provides insights on the use of biochar in a wastewater treatment process to enhance the treatment as well as recover valuable byproducts. The chapter will discuss biochar production and properties, mechanisms involving removal of organic and inorganic compounds from the effluent phase, and role in activated sludge treatment and anaerobic digestion.

2. Biochar properties for wastewater treatment

Biochar is a carbon-rich solid material produced from biomass through a thermochemical process called pyrolysis. During pyrolysis, lignin, cellulose, hemicellulose, fat, and starch in the feedstock are thermally broken down forming three products: biochar (solid), bio-oil (partly condensed volatile matter), and non-condensable gases (CO_2 , CO , CH_4 , and H_2) [26, 27]. The bio-oil and gases can be captured to produce energy and depending on the feed valuable coproducts like wood preservatives, food flavoring, adhesive, or biochemical compounds [28]. The yield of biochar and the properties, however, depends on the pyrolysis condition. Slow pyrolysis at moderate temperature (350–500°C) and slow heating rate results in higher yield (30%) of biochar than around 10% or less yield with fast pyrolysis (600–700°C and fast heating rate) or gasification (temperature 700°C or above) [29]. The feedstock type and pyrolysis condition used during the production of biochar notably change the physiochemical properties such as surface area, polarity, atomic ratio, pH, and elemental composition [25, 30, 31]. These properties determine the effectiveness of biochar in wastewater treatment.

Biochar has wide applications in water and wastewater treatment because of its distinctive characteristics, for example, adsorption capacity, specific surface area, microporosity, and ion exchange capacity [30, 32]. The removal mechanisms of different pollutants are governed by their interactions with various attributes of biochar, which depends on pyrolysis temperature and feedstock type [33]. Pyrolysis temperature greatly affects the properties of biochar. The increase in pyrolysis temperature results in higher carbon content, hydrophobicity, aromaticity, surface area, and microporosity in biochar [34]. Similarly, the pH of the biochar increases with increasing pyrolysis temperature due to enrichment of ash content in the biochar [35, 36]. High-temperature (>500°C) biochar has low polarity and acidity due to loss of O- and H-containing functional groups [34]. Lower pyrolysis temperature (<500°C) facilitates partial carbonization, thus yielding biochar with smaller pore size, lower surface area, and high O-containing functional groups [36]. Lower temperature biochar contains a higher content of dissolved organic carbon, relatively low polarity and C/N ratio [30, 34, 37].

Biochar often comprises of both positively and negatively charged surfaces (zwitterionic) [34, 35]. The negatively charged functional groups contribute to cation exchange capacity (CEC) whereas anion exchange capacity (AEC) is also exhibited by O-containing functional groups (oxonium heterocycles) in biochar [36, 38]. Oxygen (O) containing alcohol, carbonyl, and carboxylate functional groups are generally believed to contribute to biochar cation exchange capacity because they carry a negative charge and serve as Lewis bases for the sorption of cations. Whereas, it is believed that oxonium functional groups contribute to pH-independent anion exchange and that both pyridinic functional groups and nonspecific proton adsorption by condensed aromatic rings contribute to pH-dependent anion exchange capacity in biochars [38].

Biochar derived from woody biomass and crop residues has a higher surface area compared to that of solid municipal wastes and animal manure [30]. Apart from the usual pyrolysis method, different engineering methods have been developed and used to expand biochar's applications. Engineered biochar is the derivative of biochar that is modified by physical, chemical, and biological methods to improve its physical, chemical, and biological properties (e.g., specific surface area, porosity, cation exchange capacity, surface functional group, pH etc.) and its adsorption capacity [37, 39, 40]. Some of the modification includes anaerobic digestion of feedstock before pyrolysis, steam/gas activation, pyrolysis using microwave heating, ball milling, magnetic modification, chemical modification using hydrogen

peroxide, alkali or acid, and impregnation/coating with chemicals [41]. The detail about the modified biochar for wastewater treatment will be discussed in the following sections.

2.1 Biochar modification

Researchers have discussed several methods for modifying the properties of biochar [42]. These methodologies include treatments with steam, acids, bases, metal oxides, carbonaceous materials, clay minerals, organic compounds, and biofilms [43].

2.1.1 Physical activation of biochar

Physical activation methods such as steam activation involve high-temperature steam forced through the pores of the biochar. Steam activation, which is carried out after pyrolysis, is a common modification method used to increase the structural porosity of the biochar and remove impurities such as products of incomplete combustion. According to [44], higher water flow rates and longer activation times at 800°C increased the sorption of Cd, Cu, and Zn on the surface of biochar from poultry manure feedstocks pyrolyzed at 700°C. In another study, comparison of Cu²⁺ adsorption for biochar from *Miscanthus* before (500°C pyrolysis) and after (800°C) steam activation showed no significant change [45]. It was found that steam activation of the biochar increased the surface area and aromaticity alongside a decrease in the abundance of functional groups [45]. Similarly, steam-activated biochar from pine sawdust increased the surface area but had little effect on the surface functional group as a result of which adsorption capacity of biochar for phosphate was reduced due to electrostatic repulsion by the negatively charged surface of biochar [46]. The steam-activated invasive plant (*Sicyos angulatus* L.)-derived biochar produced at 700°C showed 55% increase in sorption capacity of veterinary antibiotics (sulfamethazine) compared to that of nonactivated biochar produced at the same temperature [47]. Hence, steam activation could be a process for increasing the porosity and surface area of biochar along with aromaticity to obtain better adsorption of inorganic material in the wastewater.

2.1.2 Chemical activation using acidic and alkaline solutions

The biochar activation using acidic solutions forms carboxylic groups on the biochar surface [48] and develops micropores, thus increasing the surface area [49]. The increase of oxygenated functional groups on biochar surfaces increases the potential of biochar to bind positively charged pollutants through specific adsorption chemically. The pH dependence of Cu²⁺ sorption capacity for HNO₃-activated cactus fiber biochar indicated chemical sorption on oxygen-containing functional groups on the biochar surface [48]. Higher O/C ratio in the post-activation of rice straw with H₂SO₄ and HNO₃ showed evidence of oxygen-containing functional group incorporated into the carbon structure [50]. Acid treatment of pine tree sawdust with diluted H₃PO₄ prior to pyrolysis increased the surface area, the total pore volume, and volume of micropores area along with P-O-P incorporation in the C structure [51]. This increased the Pb sorption capacity of the phosphoric-treated biochar by 20% in comparison to a nontreated sample, mainly due to phosphate precipitation and surface adsorption [51]. Similarly, almost double increase in cation exchange capacity was observed for pinewood biochar treated with 30% H₂O₂ because the oxygen-containing functional groups in the surface of biochar,

which were more abundant in the activated biochar, exchanged with cations in solution [52]. Treating a hydrochar, a carbon-enriched solid produced from hydrothermal carbonization of peanut hull, with a 10% H₂O₂ solution increased Pb sorption capacity compared to the unmodified hydrochar, which can be attributed to a greater abundance of carboxyl functional groups that can form complexes with Pb [53]. However, the introduction of acid or oxidizing agents dissolves mineral components (CO₃²⁻, SiO₄²⁻, PO₄³⁻) in the biochar structure and removes them from the biochar matrix. These minerals in biochar are particularly important for the removal of metal cations from water due to precipitation [54], the affinity of which could be reduced by the acid treatment.

Activation of biochar using alkali (most commonly KOH and NaOH) increases adsorption by increasing porosity, surface and oxygenated functional group at the surface. Oxygenated functional groups provide proton-donating exchange sites where cation such as Pb²⁺ adsorbs chemically [55]. The activation of ipomoea plant biochar with KOH, followed by pyrolysis (350–550°C) demonstrated an increase adsorption of Cd from aqueous solution [56]. Further evidence of kinetics of sorption fitting a pseudo-second-order model and thermodynamic studies indicating spontaneous endothermic process showed that Cu sorption on KOH-activated biochar was due to chemical adsorption [57]. The adsorption capacity of As(V) on municipal solid waste biochar was increased by 1.3 times after activation with 2 M KOH [58]. It can be concluded that activation by alkali greatly enhanced the surface area and alteration of the functional group at the surface.

2.1.3 Biochar-based composites

The biochar composites are prepared by embedding different materials into the biochar structure pre- or post-pyrolysis. Generally, biochar has a higher surface area, high pH, and a negative surface charge. This facilitates specific adsorption of metal ions via oxygenated functional groups, electrostatic attraction to aromatic groups, and precipitation on the mineral ash components of the biochar. But at the same time biochar is usually a poor adsorbent for oxy-anions contaminants like NO₃⁻, PO₄³⁻, and AsO₄³⁻ [44]. This can be improved by the homogenous spread of metal oxide on biochar surfaces. It can be done by soaking biochars or the feedstocks in a solution of metal nitrate or chloride salt solution (common examples FeCl₃, Fe, Fe(NO₃)₃, and MgCl₂) and heated under atmospheric condition within a temperature range of 50–300°C. This process ensures removal of nitrite and chlorine leaving behind metals in the biochar matrix. Ca-, FeO-, and Fe³⁺-modified biochar from soaked rice husk and municipal biomass in CaO, iron powder, and FeCl₃ respectively, increased the capability of biochar to remove As(V), but not as high for Cr(VI), from aqueous solution [59]. Taking into consideration that one of the main mechanisms for Cr(VI) removal is the electrostatic interaction to the positively charged functional groups on the surface of adsorbents, high Cr(VI) removal is observed at low pH values [60]. It is rather possible that the high pH values of the RH-Ca2p, RH-Fe0, and SW-Fe0 solutions are related to the deprotonation of their functional groups and the repelling of the negatively charged Cr(VI) [60]. Similarly, a 20-time increase in the sorption of As(V) was observed when corncob biochar was modified with Fe(NO₃)₃ [61]. Despite the lower surface area, modification of biochars from garden wood waste and wood chips as well as corncob showed the increased PO₄³⁻ sorption by a factor of 12–50% [58]. Further research has been carried out for preparing biochar-based composites by impregnation or coating the surface of the biochar with metal oxides of Al, Mn, and Mg [58]; clay minerals [62]; complex organic compounds, such as chitosan [63] or amino acids [64]; or inoculation with microorganisms [65].

Thus, the selection of biochar and modification methods for the application in wastewater treatment requires a considerable understanding of the biochar properties and mechanism by which it supports the treatment process at different stages of wastewater treatment.

3. Role of biochar use in wastewater treatment process

Biochar could be used at different stages of wastewater treatment (**Figure 1**) to improve the treatment efficiency and recovery of value-added byproducts. Biochar application in wastewater treatment could be governed by the mechanism of adsorption, buffering, and immobilization of microbial cells. If used on the treated effluents, suitably modified biochar could efficiently adsorb nutrients like nitrogen and phosphorus, which can later be used as a nutrient-enriched material for soil remediation. When used in the activated sludge treatment process, biochar could play a role for improving the treatment and settling ability of the sludge by adsorption of inhibitors and toxic compounds or provide a surface for immobilization of microbes. Addition of biochar in the biological system could eventually help to improve the soil amendment properties of the biosolid as well. As interest grows in the use of biochar in soil applications, its use in wastewater treatment could expand the value chain and create additional economic benefits [66]. The following section will discuss the role of biochar for various applications in the wastewater treatment plant.

3.1 Organic pollutant removal

In recent years, significant amount of research has been done to examine the application of biochar for removal of various organic compounds from water, which includes agrochemicals, antibiotics/drugs, polycyclic aromatic

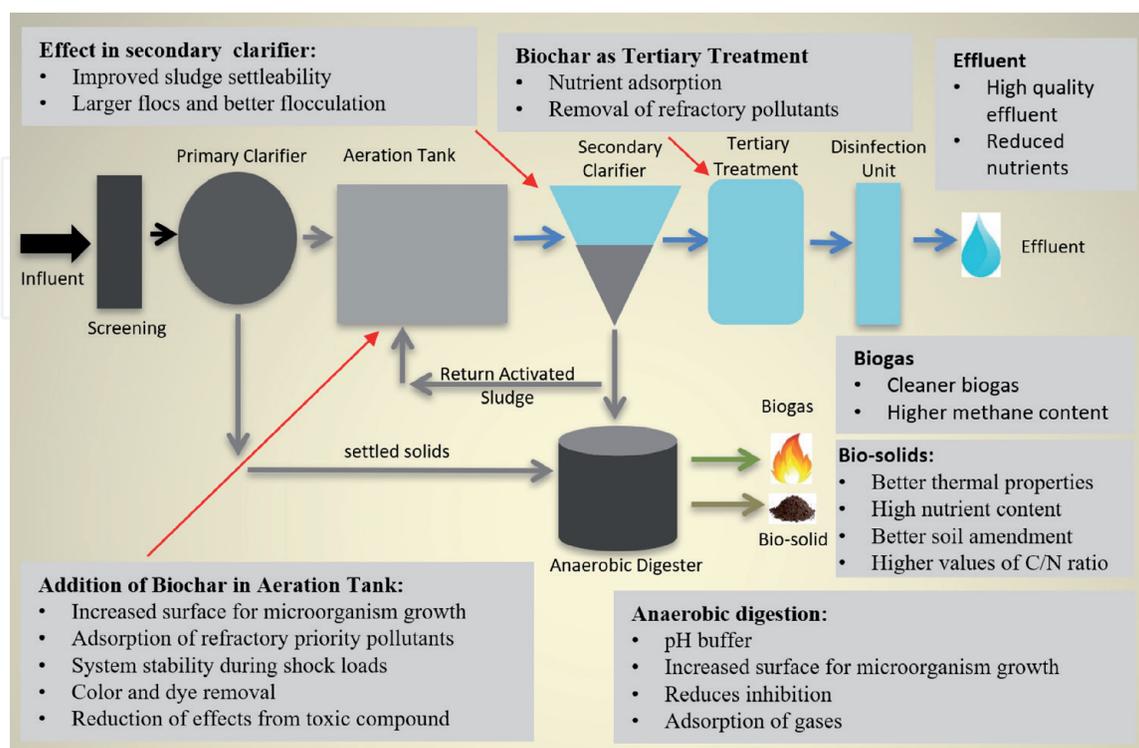


Figure 1. Use of biochar at different stages of wastewater treatment.

hydrocarbons (PAHs), volatile organic compounds or (VOCs), cationic aromatic dyes [67–70]. Similarly, removal of organic compounds present in specific waste streams such as estrogen compounds in animal manure and sewage, inhibitory compounds of biomass degradation (furfural, hydroxymethylfurfural, phenolic compounds), and toxic organic compounds in landfill leachate has been studied using biochar [71, 72]. **Figure 2** schematically shows different interactions of the organic pollutant with biochar.

Biochar produced at higher pyrolysis temperature is found better for removal of nonpolar organic compounds due to higher surface area and microporosity [30, 73]. In contrast, biochar produced at a temperature below 500°C contains more O- and H-containing functional groups; thus, they are likely to have a high affinity to polar organic compounds [26]. For example, rice husk and soybean-derived biochar (600–700°C) facilitates removal of nonpolar carbofuran (pesticide) and trichloromethylene (VOC) from contaminated water [26]. Efficient removal of pyrimethanil and diesopropylatrazine (fungicide/pesticide) was observed with red-gum wood chips and broiler litter-derived biochar at temperature >700°C, whereas the same biochar at temperature <500°C was inefficient [74, 75]. On the other hand, removal of polar insecticide and herbicide like 1-naphthol, norflurazon, and fluridone was observed with biochar produced at <300°C, due to interaction of pollutant and the functional groups of biochar [76, 77]. Likewise, higher sorption of aromatic cationic dyes like methyl-violet and methyl-blue was observed with biochar containing more O- and H-functional groups (<400°C) but the mechanism was highly dependent on pH [70, 78]. The sorption of polar antibiotic sulfamethazine (SMZ) by hardwood/softwood-derived biochars (produced at 300–700°C) has pH-dependent

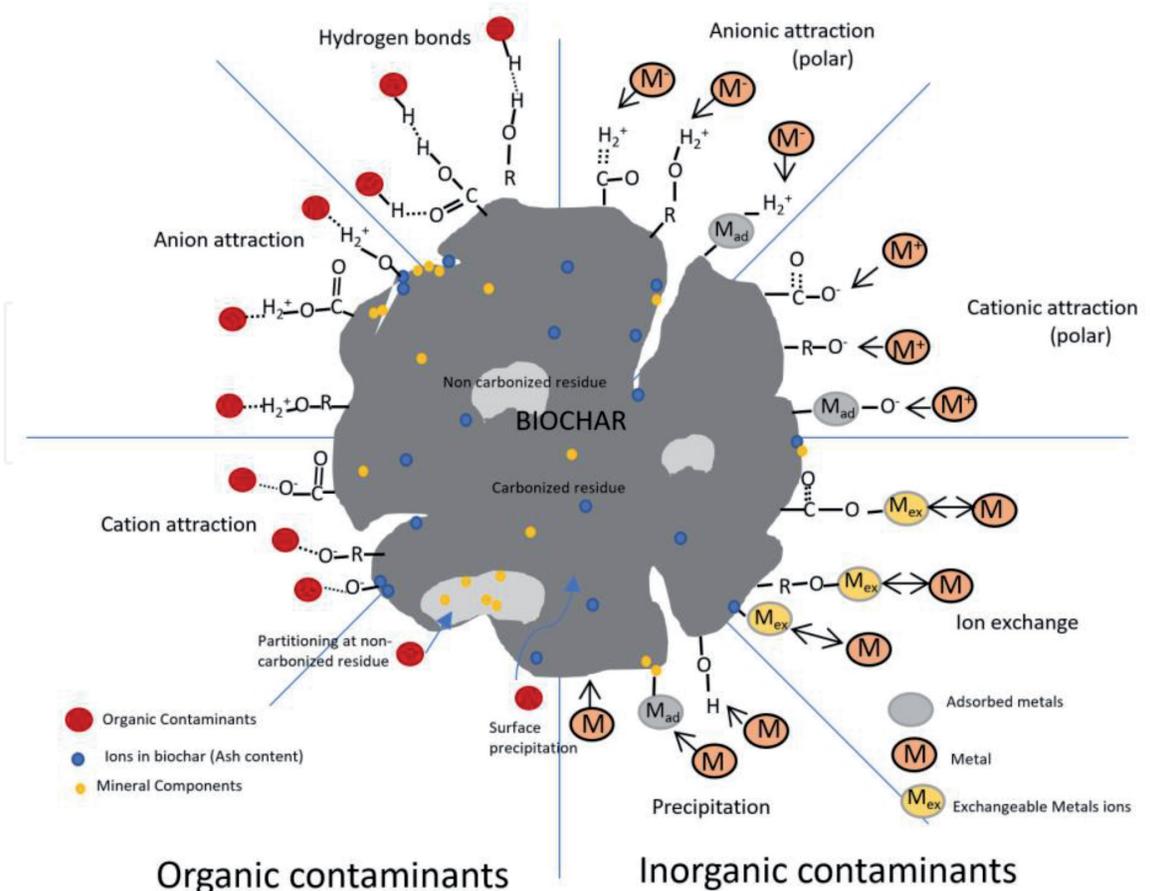


Figure 2. Biochar interaction with organic and inorganic compounds in wastewater (adapted from Ahmad et al. [33]).

interactions [79]. It can be said that pH is the most important factor for biochar interactions and removal of polar organic pollutants.

3.2 Inorganic pollutant removal

Inorganic pollutant in wastewater includes heavy metals (Cr, Cu, Pb, Cd, Hg, Fe, Zn, and As ions) and compounds like nitrate (NO_3), nitrite (NO_2), ammonium (NH_4), phosphorus (P), and hydrogen sulfide (H_2S) that cause significant risk to public health and environment [80]. Biochar produced at lower pyrolysis temperature ($<500^\circ\text{C}$) has properties that are better suited for removal of inorganic compounds. The chemical composition and the morphological structure play an important role in the sorption nature of biochar [81]. **Figure 2** summarizes the interaction methods for inorganic pollutant and biochar.

3.2.1 Heavy metals

Biochar with high organic carbon content (at non-carbonized fraction), specific porous structure, and numerous functional groups interacts with heavy metals in many ways [82]. The sorption of heavy metals by biochar is mainly by surface interaction through ion exchange and complexation between biochar functional groups (e.g., OH, COOH, R-OH) and heavy metal ions [83, 84], moreover formation of metal precipitates with inorganic constituents [83–85] and coordination of metal ions with π electrons ($\text{C}=\text{C}$) of biochar [74]. The physiochemical properties of biochar affect the adsorption throughout its matrix and are dependent on pyrolysis temperature, feedstock type, pH, and application rate. Cu^{2+} showed high affinity toward COOH– and OH– groups of hardwood and crop-derived biochars with dependency on pH and feedstock types [86]. Similarly, sida hermaphrodita-, guayule shrub-, soybean straw-, and wheat straw-derived biochars were effective for removal of Cd^{2+} , Ni^{2+} , and Zn^{2+} along with Cu^{2+} [87]. The higher efficiency of the above-mentioned biochar was due to high C and O contents, high O/C molar ratio, and polarity index, which were mainly regulated by pH [88, 89]. Alkaline biochars derived from various agricultural residues (e.g., soybean straw, corncob, cocoa husk, corn stover, switchgrass) and manure were efficient for Hg^{2+} removal. Animal manure-derived and cocoa husk biochar was highly effective for Hg^{2+} removal due to high sulfur (SH groups and sulfate) to precipitate 90% of Hg^{2+} as $\text{Hg}(\text{OH})_2$ or HgCl_2 mainly through coprecipitation with anions (Cl, O, S) of biochar [73, 90].

For Cd^{2+} , Zn^{2+} , Pb^{2+} , and Cu^{2+} dosage of biochar also affects the removal of heavy metals. The higher removal efficiency is observed with increasing biochar loading in the aqueous system, due to increased pH and surface area with biochar addition [54, 91].

3.2.2 Nitrogen and phosphorus

The high surface charge density allows biochars to retain cations by cation exchange and the high surface area, internal porosity, and presence of both polar and nonpolar surface sites on biochar enable it to adsorb nutrients [92]. In the limited studies carried out without soil, biochar has shown the absorption NH_4^+ , NO_3^- , and PO_4^{3-} despite the different charges and properties of these nutrients [93]. Some examples include digested sugar beet tailing biochar pyrolyzed at 600°C that adsorbed PO_4 ions most likely in binding sites contained in colloidal and nano sized MgO particles on the biochar surface [94]. Also, orange peel biochars pyrolyzed between 250 and 700°C removed between 8 and 83% of phosphate from solution

[95]. NH_4 was adsorbed to biochars produced from rice husk [96] and a mixture of tree trunks and branches [97], albeit weakly, as the partitioning coefficients between water and biochar were low (Freundlich coefficients of 0.251 mg g^{-1}). Similarly, NO_3^- has been adsorbed to bamboo charcoal biochar in the concentration range of $0\text{--}10 \text{ mg L}^{-1}$ [98].

3.3 Activated sludge treatment

One of the most utilized systems for treatment of municipal wastewater is biological treatment process like activated sludge system (ASS) because of its cost-effectiveness and comparatively more straightforward operation to advance systems. Activated sludge process is a suspended growth treatment where aerobic microorganism decomposes the organic matter in wastewater, which eventually settles as solids by gravity. Currently, increasing concerns are being raised about the presence of various micro-pollutants from pharmaceuticals, personal care products (PCPs), pesticides, disinfectants, and antiseptic in domestic and municipal wastewaters. These pollutants are alien to the biota in the system, and the conventional treatment process often leads to inadequate removal of these compounds. Correspondingly, discharge requirements are currently being stringent for protection of receiving waters from possible contamination and public health hazard. There have been several modifications and changes in the activated sludge system to address the problem. One such method is AS-PACT (Activated Sludge with Powdered Activated Carbon Treatment) where powdered activated carbon is added to the aeration basin of activated sludge system. The larger surface area of carbon provides various benefits including adsorption of toxic substances such as pharmaceuticals and industrial chemicals, immobilization of bacteria, and increased sedimentation of activated sludge [99, 100]. Such system, however, requires a continuous makeup of fresh carbon [101].

Despite the benefits, the higher cost of activated carbon limits its use in municipal wastewater treatment [101]. The biochar could be a low-cost substitute to activated carbon [102], but its merits are less known. The addition of biochar to a biological treatment system, such as within the aeration tank, could result in increased process stability by (a) adsorption of inhibitors (heavy metals, polycyclic aromatic hydrocarbon), (b) increasing the buffering capacity of the system, and (c) immobilization of microbial cells [103]. Limited studies done on the use of biochar in the aeration tank showed increased settling ability of activated sludge [104]. Dissolved organic matter in the biochar could also provide additional carbon to promote denitrification [105]. The availability of organic matter, however, depends on the type of biomass and pyrolysis conditions used for producing biochar. Furthermore, the cascading benefits of using biochar in activated sludge treatment could also be seen on anaerobic digestion of the sludge and in the final quality of the biosolids.

3.4 Anaerobic digestion

In the case of anaerobic digestion, the addition of biochar has shown increases in the rate and amount of biogas production [106–108]. This is attributed to the buffering properties of biochar, promoting methanogenesis for higher biogas yield [109, 110]. Several studies have suggested increases in microbial metabolism and growth because of the support provided by the biochar [107, 111]. The biochar could also play a significant role in reducing the mobility or availability of the inhibitors like heavy metals, pesticides, antibiotics, and other organic compounds by binding them in its porous structure and maintain proper microbial activity for the

digestion process [103]. Further, the adsorption of nutrients in biochar and its slow release increase the availability of nutrients to the soil while preventing leaching to surrounding water bodies, as it is prevalent in the case of biosolids [103]. Therefore, the addition of biochar in the biological system could eventually help to improve the soil amendment properties of the biosolid as well.

4. Conclusion

Biochar is a unique renewable resource, which can be used in a wide variety of applications from addressing various environmental problems like climate change, remediation of pollutants in water and soil to an alternative fuel source. The cascading use of biochar as a byproduct of pyrolysis for wastewater treatment and nutrient recycling can synergistically improve soil and water quality, carbon sequestration, greenhouse gas emissions, nutrient cycling, and fuel crisis. The approach perfectly fits the ideas of the circular economy: reuse and recycle of waste, keeping material and product in use. This approach is connected with three natural cycles: water, carbon, and nutrient and has a direct impact on energy, water, and food systems. While much work has been done in modifying the biochar for adsorption of desired organic or inorganic compounds, very less is known on its application in activated sludge treatment, anaerobic digestion, and the overall quality of the biosolids. As the benefits of the integrated use of biochar in wastewater treatment to soil application is established in this chapter, future experimental research work could verify its effectiveness.

Conflict of interest

The authors declare no conflict of interest.

Nomenclature

CO ₂	carbon dioxide
CO	carbon monoxide
CH ₄	methane
H ₂	hydrogen
C	carbon
N	nitrogen
O	oxygen
Cu	copper
HNO ₃	nitric acid
H ₂ SO ₄	sulfuric acid
H ₃ PO ₄	phosphoric acid
Pb	lead
H ₂ O ₂	hydrogen peroxide
P	phosphorus
Ca	calcium
Mg	magnesium
K	potassium
Na	sodium
KOH	potassium hydroxide
NaOH	sodium hydroxide
Cd	cadmium

2M	2-molar concentration
As(V)	pentavalent arsenic
NO_3^-	nitrate
PO_4^{3-}	phosphate
AsO_4^{3-}	arsenate ion
FeCl_3	ferric chloride
Fe	iron
$\text{Fe}(\text{NO}_3)_3$	ferric nitrate
MgCl_2	magnesium chloride
Ca	calcium
FeO	ferrous oxide
Fe^{3+}	ferric ion
Cr(VI)	hexavalent chromium
Al	aluminum
Mn	manganese
Cr	chromium
Hg	mercury
Zn	zinc
As	arsenic
COOH-	carboxylic acid functional group
OH-	hydroxy functional group
R-OH	carbon chain with hydroxy functional group
$\text{Hg}(\text{OH})_2$	mercury hydroxide (bivalent)
S	sulfur
H_2S	hydrogen sulfide
Cl	chlorine
SH	sulfanyl or thiol
$\text{E}^{+/-}$	ions of compound/element E
Abbreviations	
CEC	cation exchange capacity
AEC	anion exchange capacity
PAHs	polycyclic aromatic hydrocarbons
VOCs	volatile organic compounds
SMZ	sulfamethazine
AS-PACT	Activated Sludge-Powdered Activated Carbon Treatment

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